AN INFORMATION SYSTEM FOR

THE CONTROL OF BROWN

RUST IN BARLEY

P. K. Thornton, J. B. Dent
and A. C. Beck

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THE AGRICULTURAL ECONOMICS RESEARCH UNIT
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PREFACE

One of the Agricultural Economics Research Unit's traditional activities lies in the field of farm management research. Over the past decade or so there has been a steady growth in the field of systems modelling concerned with farm management applications. The recent Agricultural Economics Research Unit publications in this field include Research Report No. 133 which assessed management strategies for irrigated Canterbury sheep farms and Research Report No. 149 which investigated the relative economics of gorse control by goats or chemical methods.

The present report was written by Dr P.K. Thornton and Professor J.B. Dent (Department of Farm Management and Rural Valuation) and Mr A.C. Beck (Agricultural Economics Research Unit). The report presents an information system that can be utilised to aid farm decision making regarding whether or not to spray for brown rust in barley.

The work deserves particular note for the way in which tables have been constructed to guide the decision maker without his/her requiring access to computer hardware.

P.D. Chudleigh
DIRECTOR

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This report draws heavily in places on two papers by Thornton and Dent, published in Agricultural Systems, Elsevier Applied Science Publishers, London.

SUMMARY

Considerable scope exists for the reduction of the primary and secondary costs associated with crop protection, by the formulation of judicious fungicide application regimes. The design, building and operation of a farm-level computer based information system is described, the purpose of which is to help the farmer make rational spraying decisions. The system makes use of a simulation model built in 1978 which is capable of accurate prediction of the yield loss induced by epidemics of *Puccinia hordei* Otth on *Hordeum vulgare* L. cv. Zephyr. Extensions were made to this model to enable crop growth and disease to be projected into the future. Increased disease intensity occurs in response primarily to certain meteorological conditions; a model was built to carry out the probabilistic simulation of key weather variables.

The Bayesian revision of yield reduction probability distributions provides the conceptual basis for the information system. The two strategies open to a decision maker as the season proceeds, those of spraying immediately and delaying application, were assessed using various decision criteria. Validation work was performed. Risk attitudes for a small sample of cereal growers were investigated; the importance of risk in the spraying decision is shown to be marginal. A low-cost method of implementation is illustrated; decision tables are derived on the basis of extensive simular experimentation and representative attutudes to risk. It is concluded that such an information system has the potential for the provision of timely recommendations.

KEYWORDS: Simulation; Leaf Rust; Barley; Information; System; Decision; Fungicide; Utility; Risk; Bayesian; Computer Model.

CHAPTER 1

INTRODUCTION

Brown rust of barley, caused by the pathogen Puccinia hordei Otth, is widespread in New Zealand, and associated national yield losses have to be expected in most years; occasionally these will be severe (Arnst, Martens, Wright, Burnett and Sanderson, 1979). Rigid conformance to a policy of always or never spraying for the disease is likely to be wasteful, either of fungicide or of the barley crop. If a prophylactic control program is not to be followed, the control strategies open to a decision maker midway through the season are essentially limited to the application, or not, of particular chemicals. Brown rust tends to occur late in the growing season if at all; information relating to the spraying decision would generally be useful to a decision maker in the Southern Hemisphere from mid-December through to February, depending on the date of planting of the crop and the date of disease onset.

An information system, designed to help the farmer make a spraying decision, is described in this report; it is based on the rationale that spray be applied only when it becomes expedient: both the primary (on-farm) and the secondary (social and environmental) costs associated with chemical applications should be avoided, if possible. The importance of risk in the information system is examined, using the results of a survey of the risk attitudes of a small number of cereal growers in the South Island. A method of implementation is then outlined, involving the derivation of spray tables for various combinations of field conditions; an estimate is made of the monetary value of such decision tables. The report is concluded with a discussion of the nature of biological simulation models and the information systems within which they may be embedded.

CHAPTER 2

DESIGN AND OPERATION

2.1 Brief System Description

The information system is conceptualised in Figure 1. It consists of two distinct parts: the essential part of the first can be considered a black box that will produce estimates of crop yield loss related to the epidemic, crop growth being simulated forward from any time T in response to a particular weather sequence; the second is concerned with the economic comparison of control of the epidemic on the one hand, and of allowing the epidemic to proceed unchecked on the other. The costs and benefits of each strategy are then translated into a recommendation to spray immediately or to wait. The system is capable of providing a succession of strategy comparisons through the season. The black box stochastic simulator used in this case is BARSIM (Teng, 1978; Teng, Blackie and Close, 1980). At a point in time T when the disease is first recognised in the crop, the date of sowing, the date of T, and the historical weather records for the period between these two dates, are entered into the simulator. BARSIM will then, with forward simulation of key weather variables, determine crop growth and disease spread until just prior to harvest. The encounter with BARSIM at time T will ideally involve the simulation of crop growth and disease progress until harvest over a large number of possible weather sequences. Data from each run within an encounter are presented to a multiple-point yield loss function. Essentially, this is a best-fit regression equation established from previous crop information relating disease status at various crop growth stages to the final yield loss percentage. In this case, disease status on the top two leaves of the primary tiller at the sequential crop growth stages 58, 64, 73 and 83 (Zadoks, Chang and Konzak, 1974) was found to be the best indicator of subsequent crop loss (Teng, 1978).

An encounter with the information system will then produce a probability density function (pdf) of yield loss estimates from the known situation at time T. As T moves from the time of first recognising the disease in the crop to the final growth stage, some of the originally projected weather sequence becomes historical (Figure 2). Disease status

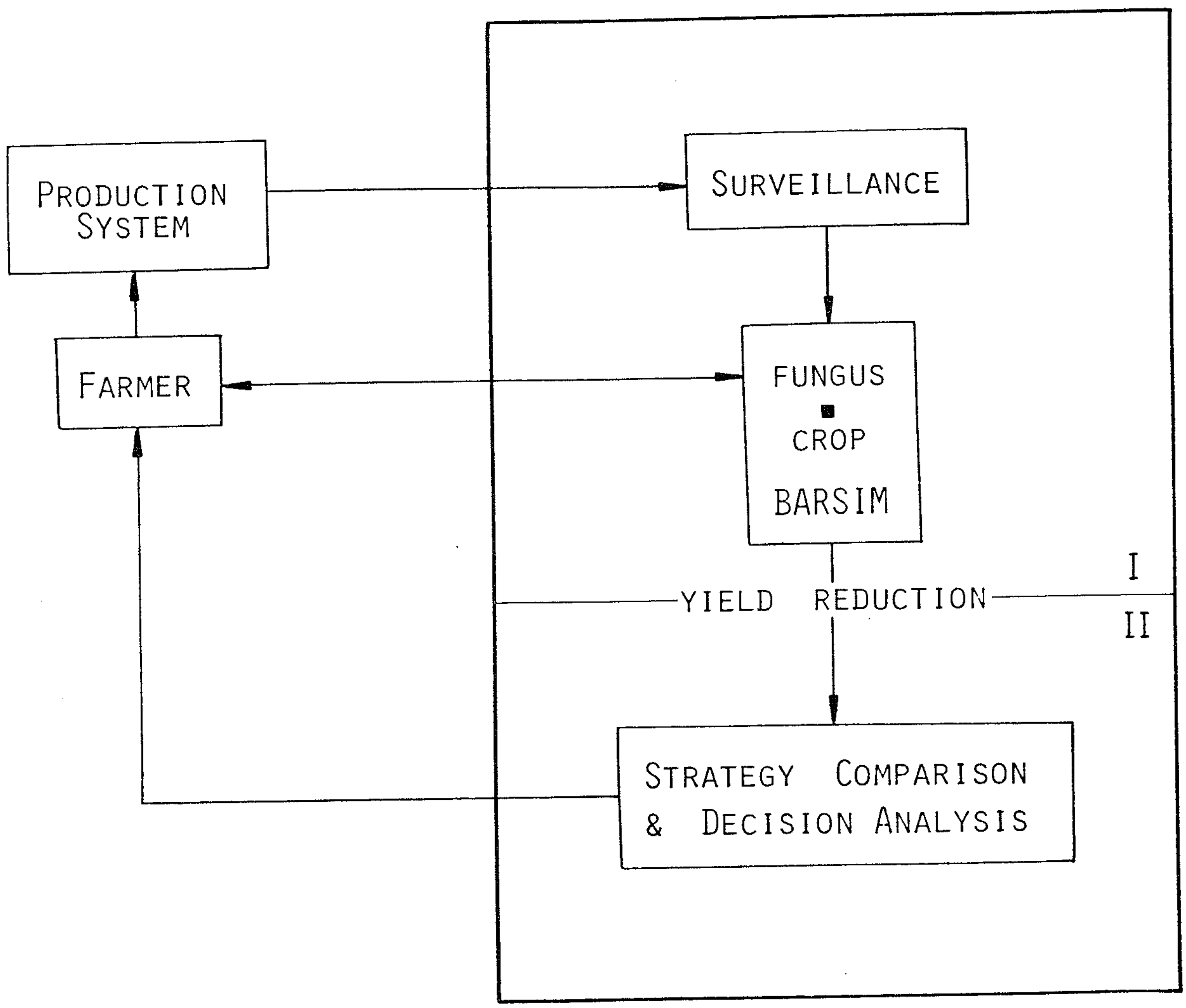

FIGURE 1. Barley Leaf Rust Information System

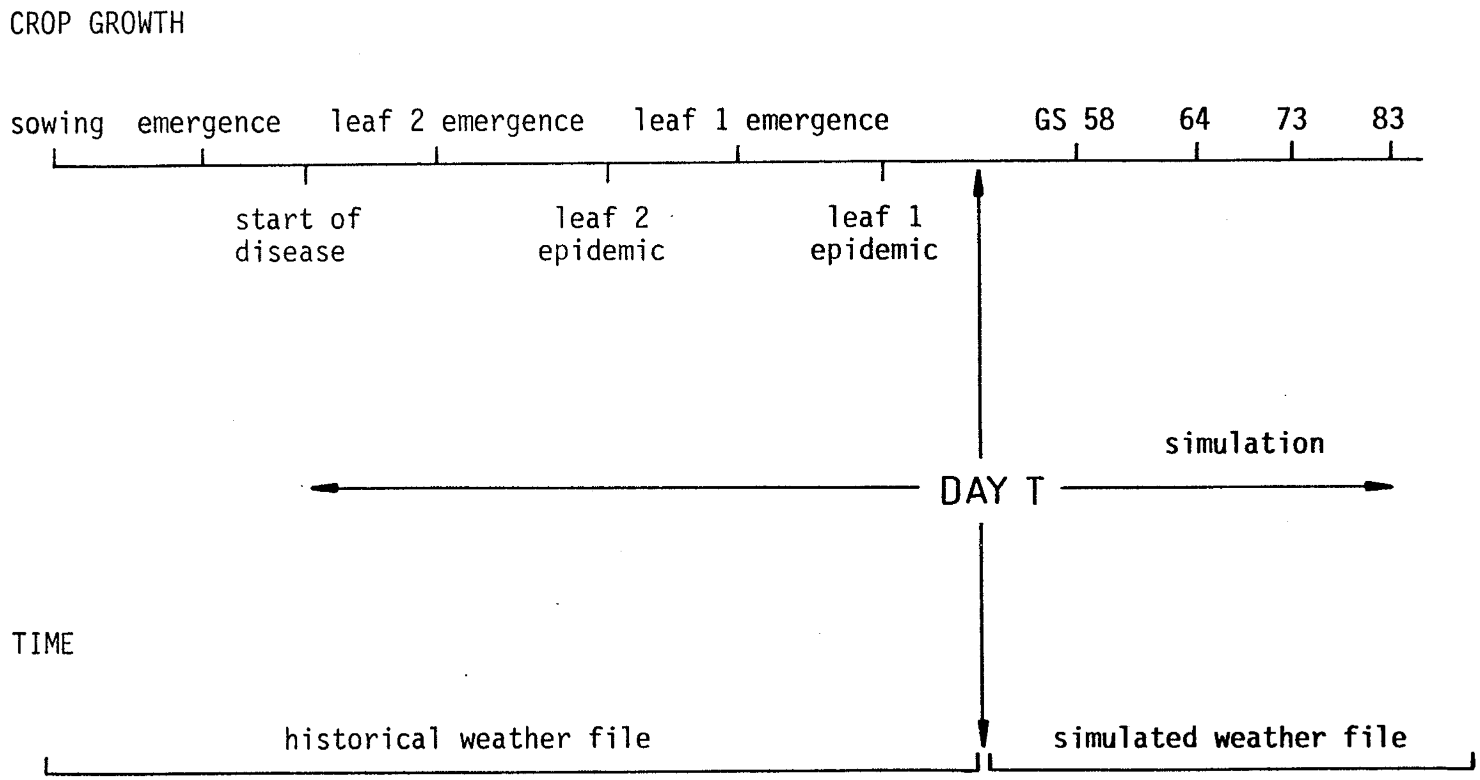

FIGURE 2. Weather Files and Simulated Time

and crop growth may also be updated as the season proceeds; at time T, the observed and simulated epidemic progress curves are equated, and the observed date of the most recent growth stage attained is entered over the simulated date of the same occurrence.

The simulation of disease development proceeds on a daily basis, and depends on the weather sequence, particularly leaf wetness (to allow spore germination), and a feed-back mechanism which allows the disease to spread only at the expense of green leaf tissue. Crop growth is simulated using a degree-day system with a 5 ^{o}C base similar to that of Ritchie, Dent and Blackie (1978) for wheat. Computer files are available to accommodate historical weather information up to time T. The information system, FUNGINFO[1], accommodates a series of computer routines that permit key weather parameters to be simulated from time T to harvest: these are average temperature, minimum grass temperature, rainfall, the occurrence of dew, and sunshine hours. Certain interdependencies, illustrated in Figure 3, are defined to exist between these weather variables. For example, dew occurrence and rainfall occurrence are assumed to be independent binary events, each dependent on the occurrence of dew or rainfall on the preceding two days. Average ambient temperature on any day $\underline{i}$ is correlated with the temperature on the previous day, and is dependent also on the occurrence of rainfall on days $\underline{i}$ and $\underline{i}$-1. Daily values of average temperature and minimum grass temperature are derived in association with random sampling from appropriate normal distributions or, if normality is not a tenable assumption, from Johnson distributions (Thornton and Beck, 1984). Leaf-wetness (and hence spore germination) is brought about by dew occurrence or by rainfall in excess of ten mm over a 24-hour period (Teng, 1978). The actual probabilities and distribution parameters used to simulate weather on any day $\underline{i}$ are dependent on the half-month within which day $\underline{i}$ falls; fourteen sets of these parameters may be accessed, for the fourteen half-months in the spring and summer period September to March.

2.1.1 Revision of probabilities

For any growing season, there is some probability of there being a damaging attack of barley leaf rust, such that control of the fungus is

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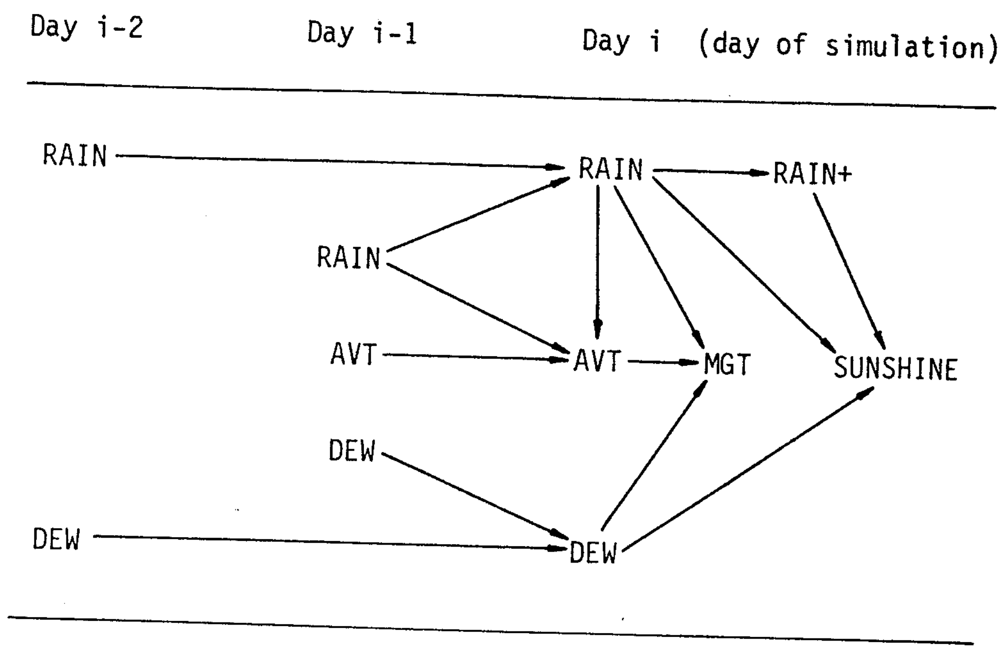
1 FUNGINFO - an acronym for fungus information system.



AVT average ambient temperature
MGT minimum grass temperature
DEW dew occurrence

RAIN rain occurrence
RAIN+ rainfall over 10 mm
SUNSHINE sunshine hours

FIGURE 3. Weather Variable Interdependencies

economically viable. There exists prior to sowing an entire probability density function of yield reduction estimates, which is largely unchanging from one season to the next (if the same cultivar is grown). It is clear that epidemic variability is proportional in some way to the forthcoming weather; over any season, as this uncertain weather is replaced by historical records, a succession of new, revised outcome density functions may be envisaged, reflecting the effect of the weather that has actually occurred (and thus has no uncertainty attached).

Such an approach is implicitly Bayesian; the prior probability density function of yield reduction outcomes is that which exists for any season before disease onset. As disease is observed later in the season, an encounter at time T with the information system produces a revised pdf of yield reductions, which may then be viewed as the posterior pdf, derived by the incorporation of a certain amount of known weather up to the date of simulation. A large number of epidemics may be simulated by subjecting the observed epidemic (up to time T) to a variety of possible weather sequences from time T to GS 83, to derive a discrete approximation to this hypothetically continuous yield reduction distribution.

2.2 System Operation

The operation of the information system on a single farm may be illustrated by reference to a specifically designed field trial, the cropping details for which are given in Table 1. The yield of the chemically controlled, disease-free treatment of the trial was 3.4 t/ha; the treatment in which leaf rust was allowed to proceed unchecked suffered a yield reduction of 11.8 per cent attributable to *P. hordei*.

As an illustration, five encounters with the information system were carried out, the first taking place with time T equated with the date of disease onset (15 January). For each of fifty replicates, a weather sequence was simulated from 15 January through to the date of attainment of GS 83; crop growth was modelled from time T using the degree-day system in conjunction with simulated values of average ambient temperature. The epidemic was projected forward on the basis of the historical date of disease onset and the onset severity recognised in the field; the

TABLE 1

Cropping Details, Trial T2, 1979/80: Uncontrolled Treatment

Crop Detail	Date	Disease Detail	Date
Sown	20 December	Disease onset	15 January
Emerged	28 December		
Leaf 2 emerged	21 January	Leaf 2 onset	28 January
Leaf 1 emerged	4 February	Leaf 1 onset	18 February
Growth stage 58[a]	13 February		
Growth stage 64[a]	18 February		
Growth stage 73[a]	23 February		
Growth stage 83[a]	27 February		
Harvested	30 March		

[a] Decimal scale (Zadoks, Chang and Konzak, 1974)

simulated severities on the top two leaves at the four relevant growth stages provided the disease data for estimating the percentage yield reduction due to leaf rust for each particular weather sequence. The fifty epidemics, each simulated with a different randomly generated weather sequence, provided an approximation to the yield reduction percentage distribution applicable at the time of encounter.

The second encounter was simulated as taking place two weeks later, with time T as 31 January; the onset of disease on leaf 2 was thus historical, having taken place on 28 January. Again, fifty epidemics were simulated, but for each, the weather sequence which actually occurred over the period up to 30 January was used, along with the (historical) date and status of the onset of disease on leaf 2 of the primary tiller. Crop growth and weather sequences from 31 January to GS 83 attainment were simulated.

The results of five such sequential encounters, in terms of the mean and variance of each simulated yield reduction percentage distribution, are shown in Table 2. The last entry in the table shows the yield reduction obtained when the leaf rust simulation model was run with entirely historical weather and crop growth data. With no weather uncertainty, there was no epidemic variability, and the leaf rust model was run deterministically; this value of yield reduction percentage was therefore taken as the (simulated) historical yield loss attributable to the disease. Frequency histograms for each encounter are shown in Figure 4, illustrating the changing spread of estimated yield reduction percentages. It may be noted that disease updates were not performed for these encounters; the pdf revisions were thus almost wholly dependent on successive reductions in the length of the simulated stochastic weather sequences.

2.2.1 Strategy assessment

If money payoffs are assumed to measure the consequences of decisions adequately, then decision analysis between alternative actions is unequivocal: the strategy exhibiting the highest expected monetary value (EMV) will be chosen. The two strategies "spray now" (S) and "do not spray" (NS) were assessed in relation to all the encounters in Table 2. The break-even yield reduction percentage, Y_B, where the costs of not spraying are exactly equated with the net benefit of spraying, is given by:

TABLE 2

Encounter Results from Trial T2

Encounter	Time T	Yield Reduction Percentage Distribution mean	variance
1	15 Jan	6.6	136.8
2	31 Jan	11.9	230.3
3	10 Feb	21.6	186.6
4	18 Feb	17.8	25.9
5	25 Feb	14.7	0.8
(All-historical weather		13.9	-)

(observed yield loss with no control = 11.8%)

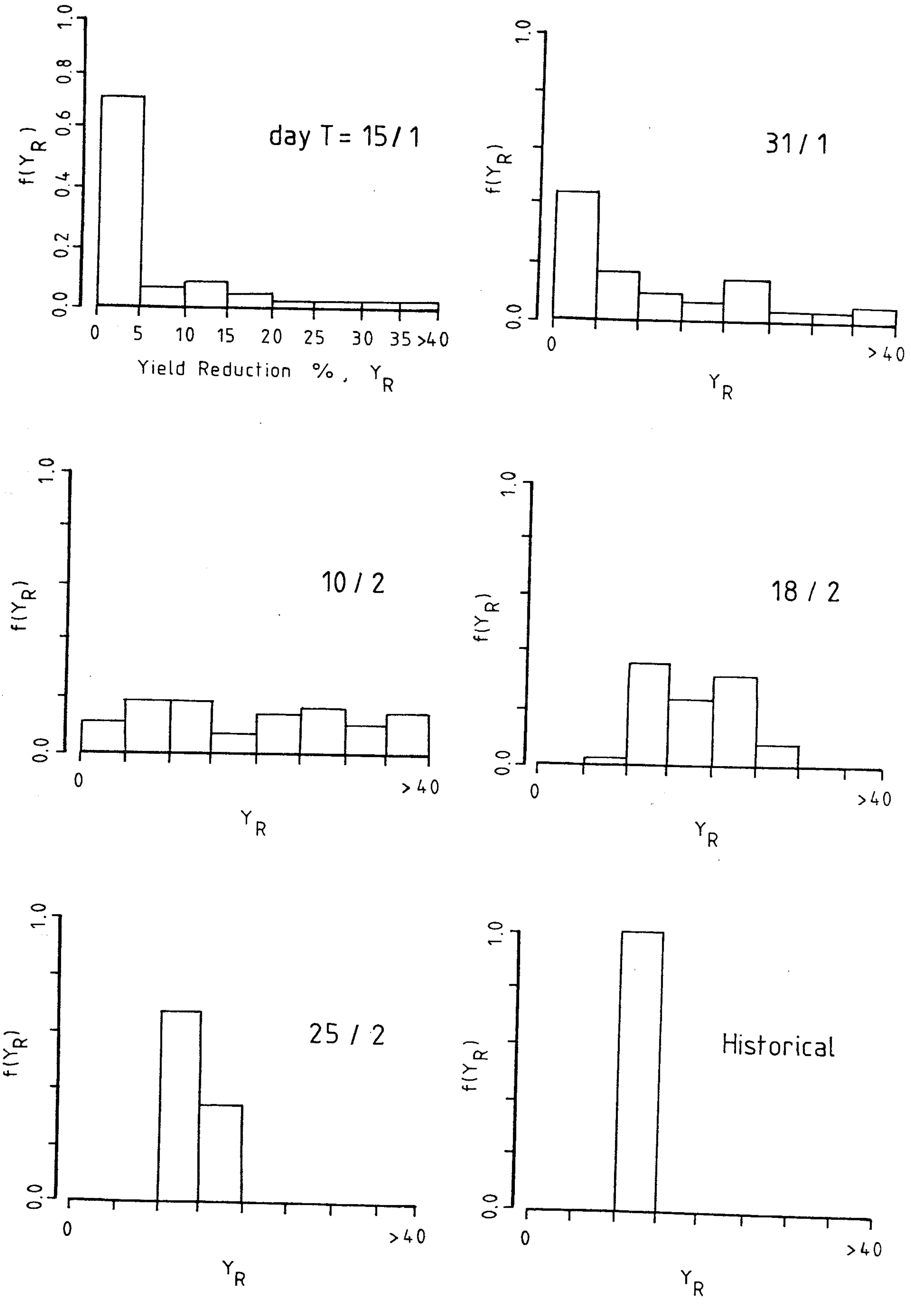


FIGURE 4. Yield Reduction Frequency Histograms, Trial T2

(1) $$Y_B = W + (100(M+A)/PY),$$

where W is the percentage yield loss brought about by wheeling damage,

M is the spray material cost,

A is the spray application cost,

P is the revenue from barley per tonne, and

Y is the yield of the cereal, assuming that spraying leads to complete control of the rust.

For a representative set of costs (with P = \$185/t, W = 2.5%, M+A = \$28.45/ha), the yield obtained in the disease-free treatment corresponding to trial T2 was equivalent to a break-even yield reduction of approximately 7 per cent. Any simulated yield reduction pdf with an expected value, $E[Y_R]$, greater than the break-even reduction will lead to a recommendation to spray; conversely, if $E[Y_R]$ is less than Y_B, the recommendation will be not to spray.

Historically, spraying was warranted for trial T2 (Table 2), and the correct recommendation was identified by the information system relatively early in the epidemic; spraying was prescribed by 31 January, four days prior to the emergence of the flag leaf. Further validation of the information system proceeded on this basis.

2.3 Assessment of the Information System

Two major considerations were identified as affecting the usefulness of the information system: firstly, the ability of the system to be used in an early-warning capacity, identifying those situations where the potential exists for the build-up of damaging levels of disease, and secondly, the ease or otherwise with which the system could be used by an individual farmer, in relation to the collection of input data.

2.3.1 Validation

A limited amount of validation work was performed with FUNGINFO. The results of encounters with three additional trials similar to trial T2 are shown in Table 3. The correct recommendation was identified for all trials a few days after flag leaf emergence at the latest. The use of

TABLE 3

Yield Reduction Distributions for Three Additional Trials

Trial	Time T		Yield Reduction, % mean	variance
T1	24 Dec	disease onset	5.2	146.6
	1 Jan		7.6	235.0
	9 Jan	one day post-GS 58	11.6	70.2
	16 Jan		10.7	23.8
	20 Jan	two days prior to GS 83	11.2	17.3
		(observed yield reduction = 11.6%)		
T3	16 Dec	disease onset	0.8	9.5
	21 Dec		0.9	2.4
	27 Dec	one day prior to GS 64	0.7	2.6
	1 Jan		1.9	2.5
	5 Jan	three days prior to GS 83	1.8	2.4
		(observed yield reduction = 1.7%)		
T4	23 Dec	disease onset	10.8	405.8
	3 Jan		8.8	371.1
	24 Jan		16.5	294.7
	31 Jan	GS 64	19.0	235.3
	7 Feb		17.9	77.5
	12 Feb	two days prior to GS 83	18.8	50.2
		(observed yield reduction = 24.1%)		

trials T3 and T4 would not normally be allowed in an objective validation process, since data from these trials were used in the construction of BARSIM-I itself. However, results of the encounters carried out using disease and crop growth data from these field trials illustrate the revision of the yield reduction distribution for epidemics of widely disparate terminal severities.

In terms of the probability density function of yield reduction percentages, a timely recommendation is most likely to be produced when close successive encounters with the information system bring about large changes in the variance or the mean (or both) of the yield loss pdf. The rapid revision of the pdf may be expected to be facilitated by the incorporation of disease updates, whereby the observed and simulated disease severities on the day of the encounter are equated. Several mechanisms for bringing about this updating of disease were developed, but no totally suitable method was found because of the nature and structure of BARSIM. Improvement in the experimental data base is needed if a satisfactory solution to this problem is to be found.

The revision of the yield reduction pdf is dependent also on the quality of the probabilistic weather series used in the projection of disease epidemics. The present weather parameter simulator could gainfully be modified, or use could be made, for example, of short-term weather forecasts in revising the frequency probabilities in a Bayesian fashion. With regard to the first alternative, long-period dependencies between weather variables were not taken into account; rather, independence was assumed to exist for all variables between periods of a half-month (Figure 3). This is likely to be an overly-simplistic assumption. For example, recent summer drought conditions in Canterbury have highlighted the vagaries of rainfall amount over long periods of time, although it may be noted that no autocorrelation could in fact be detected for rain occurrence between successive 15-day periods for the twelve years of historical records considered (Wald-Wolfowitz runs test $\alpha = 0.15$). It is apparent that the generation of weather variable time series which took half-month autocorrelation into account could become extremely complex.

Two factors in particular support the general contention that an information system similar in design to FUNGINFO may be capable of the provision of timely crop protection recommendations:

- the late season propensity of *P. hordei* epidemics considerably shortens the length of time over which uncertainty (hence variability) is exhibited in relation to a complete growing season;
- the movement forward by a few days of time T was capable of bringing about a large reduction in the variance of the yield reduction pdf, even in the absence of accurate disease updating.

A binary decision-making aid has a large measure of inherent robustness, in that small inaccuracies in detail do not automatically render the resultant decision wrong; such a feature should be able to be used to advantage in advising farmers about the use of pesticides.

2.3.2 Input data

Use of FUNGINFO on an individual interactive basis necessitates that certain data be available. In particular, historical weather records are required, up to the day of encounter, time T (Figure 2). In addition, the user should have up-to-date information relating to the status of disease in his paddock, for updating the simulated epidemic progress curves. A user of the information system might reasonably be expected to carry out his own disease assessment. In the early stages of the epidemic, it is possible to measure disease intensity as an incidence, and then convert this reading to a percentage severity. Provision exists in FUNGINFO for accepting field observations either as incidence or as severity readings. Disease sampling entails a considerable input on the part of the user; however, formal or informal farmer training in disease recognition and assessment has been shown to be a workable and cost-effective method of helping to ensure that this effort is not wasted in the production of untimely or insufficiently accurate observations (Zadoks, 1981; Menz and Webster, 1981). A considerable constraint is imposed by the fact that barley cropping in New Zealand is a relatively extensive enterprise; farmer input essentially has to be minimised. Problems for potential users of the information system may arise in relation not only to the provision of disease data, but also to the requirement for access to substantial computing facilities. These problems may be overcome in part through a suitable method of information system implementation. Such a method is illustrated in Chapter 4, whereby spraying recommendations may be provided in conjunction with minimal input on the part of the user, without the requirement of access to computing facilities.

CHAPTER 3

TREATMENT OF RISK

The expected monetary value (EMV) rule implies risk neutrality on the part of the decision maker; it is simple to apply, and the resultant recommendation, to spray immediately or to delay application, is unambiguous. Although the great majority of agricultural producers are not risk neutral (Anderson, Dillon and Hardaker, 1977), there would appear to be some trade-off necessary since greater complexity will result from incorporating risk on a personal basis into the strategy assessment procedure. The principal subject addressed in this Chapter is whether the recommendations produced using a decision criterion which takes specific account of risk are sufficiently different from those produced using the EMV rule, to justify the increase in complexity which results for the user of the information system. The results of a survey designed to elicit the risk attitudes of a small number of decision makers are used, in conjunction with simular experimentation, to assess the importance of risk in the decision making process for what, under New Zealand conditions, is a relatively extensive farm enterprise.

3.1 Representation of Risk Attitudes

3.1.1 Expected utility

A voluminous literature has arisen over the last thirty years or so in connexion with the basic observation that the behaviour of diverse decision makers is not particularly well explained in terms of the maximisation of expected profits. The expected utility model, hypothesis or dogma (von Neumann and Morgenstern, 1947) has received much attention, and numerous variants have been proposed in attempts to capture the essence of decision makers' actions when faced with prospects whose outcomes are uncertain.

The expected utility (EU) model *per se* has received substantial criticism. A number of studies have shown that the axioms on which the model is built are frequently and knowingly violated by presumably rational individuals (see, for example, MacCrimmon, 1968; Slovic and Tversky, 1974; Kahneman and Tversky, 1979). Leaving aside the purely positivistic viewpoint (that which Schoemaker (1982) terms "postdictive") which holds that such failures in the assumptions are unimportant, the operational adequacy of the EU model is also open to doubt. The lack of consistent conclusive results (Robison, 1982) is probably not surprising, in view of the hypothetical basis of the model.

There is little choice for the pragmatist, however; the incorporation of risk in any internally consistent, formalised fashion appears to necessitate the use of utility theory in some guise. For the present, the EU model may be expected to continue to serve as an approximation to the explanation and prediction of decision makers' behaviour under uncertainty.

The expected utility model, therefore, was used to incorporate risk into the decision making process within the barley leaf rust information system.

3.1.2 Choice of utility function

The risk attitudes of twelve South Island cereal growers were encoded in utility functions. It was assumed that all individuals in the sample exhibited a function of the same general mathematical form. In addition, the requirement was imposed that utility comparisons between alternative strategies could be made irrespective of the scale of the barley growing enterprise. The argument of the utility function, therefore, was dollars per hectare. A suitable utility function was the following (Binswanger, 1980):

(2) $$U(x) = (1-s)x^{1-s}$$

The parameter $\underline{s}$ is the coefficient of partial risk aversion (CPRA), defined by Menezes and Hanson (1970) and Zeckhauser and Keeler (1970) as:

(3) $$s = (-U''(x)/U'(x))x_o$$

where x_o = the certainty equivalent of a risky prospect,

and the primes refer to the respective derivatives of the function U(x). The utility function in equation (2) exhibits a constant coefficient of partial risk aversion, as may be verified by differentiating twice with respect to $\bar{x}$ (see footnote 2 overleaf).

The utility-maximising strategy may be identified from a set of risky prospects as that one which maximises the certainty equivalent. The certainty equivalent, x_o, of a risky prospect, f(x), may be expressed in terms of the CPRA. Pratt (1964) gives the following Taylor approximation:

(4) $x_o \sim \bar{x} + (1/2)\mathrm{Var}\,[x]\,.U''(\bar{x})/U'(\bar{x})$,

where x_o = the certainty equivalent of f(x),

$\bar{x}$ = the mean, E [x] , of f(x), and

Var[x] = the variance of f(x).

In view of the highly skewed nature of the majority of the yield reduction distributions obtained using the information system, the third central moment was included; Bond and Wonder (1981) continue the expansion for a further term,

(5) $x_o \sim \bar{x} + (1/2)\mathrm{Var}\,[x]\,.U''(\bar{x})/U'(\bar{x}) + (1/6)M_3\,[x]\,.U'''(\bar{x})/U'(\bar{x})$

where $M_3[x]$ = the third central moment of f(x).

Substitution of the first three derivatives of the utility function in equation (2) into equation (5) gives

(6) $x_o \sim \bar{x} - (1/2)\mathrm{Var}\,[x]\,.(s/\bar{x}) + (1/6)M_3\,[x]\,.((s^2+s)/\bar{x}^2)$.

The certainty equivalent may then be calculated for a prospect whose first three moments are known, and for a given value of the CPRA, s.

If the prospect is riskless, the certainty equivalent is equated with the expected value; if f(x) is symmetrical, the third term of the right-hand side of equation (6) disappears.

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2 This measure of risk aversion may be related to the two measures given by Pratt (1964), the coefficients of absolute (A) and relative (R) risk aversion as follows: if final wealth consists of initial wealth w and the certainty equivalent of a new prospect, x_o, the three measures are related at the point $(w+x_o)$ by

$$R = wA + s,$$

since $A = -U''(x)/U'(x)$ and $R = Ax$. In essence, absolute risk aversion is concerned with the behaviour of an individual as w increases; it is usually assumed that willingness to accept a given fair gamble increases as wealth increases. Relative risk aversion traces behaviour as both w and the size of the prospect increase, whilst partial risk aversion traces behaviour as the scale of the prospect changes by a factor k and w remains unchanged.

3.2 Survey and Results

The coefficient of partial risk aversion, parameter s in equation (2), was estimated for each decision maker using the modified von Neumann-Morgenstern method (Raiffa, 1968; Halter and Dean, 1971; Anderson, Dillon and Hardaker, 1977). The lottery presented to each respondent was related in absolute size to the individual's expectation of the range within which his yield of barley would fall. Values of gross margin per hectare were attributed to the maximum and minimum values of the range, and these were multiplied by a factor of ten, thereby restricting the payoffs to a relatively narrow range (i.e., to barley enterprise sizes in the region of ten hectares). This was done in an attempt to preserve the approximate validity of the assumption of a constant CPRA for each individual. Each respondent was asked to choose between the 50/50 lottery comprising the two extremes of the range of gross margins and the payment of a certain fixed sum of money. The sum of money constituting this second option was varied iteratively until such time as the respondent indicated indifference between it and the lottery. The fixed amount of money was then taken as the certainty equivalent of that particular lottery.

Results of the survey are given in Table 4, in terms of the twelve values of the CPRA and the coefficient of absolute risk aversion calculated at the certainty equivalent. Eight of the subjects were risk averse to varying degrees, whilst two respondents professed risk inclination. Two subjects gave their certainty equivalents as being exactly half-way between the prospects of the lottery, presumably on purpose. A context effect was noted during the questioning procedure: for at least one subject, risk was seen to be spread by diversification of enterprises, and identification of the certainty equivalent would be dependent on the overall status of the farm business.

The range of risk attitudes sampled was wide, and appeared similar to that obtained in the study by Webster (1977) of wheat growers in Kent. The accuracy of individual estimates is open to doubt, since the elicitation procedure was crude and no checks on respondent consistency were made. However, it may be supposed that the values of the CPRA were of the right order of magnitude. A result of Binswanger (1980) may be applicable to these data: the use of real money payoffs, as opposed to

TABLE 4

Survey Results: Coefficients of Partial and Absolute Risk Aversion, for Twelve Cereal Growers

Farmer Number	Coefficient of Partial Risk Aversion, S	Coefficient of Absolute Risk Aversion, A[a]
1	-0.70	-7.8×10^{-5}
2	-0.14	-1.9×10^{-5}
3	0.00	0
4	0.00	0
5	0.76	1.0×10^{-4}
6	0.98	1.5×10^{-4}
7	1.12	1.2×10^{-4}
8	1.92	3.2×10^{-4}
9	2.22	3.1×10^{-4}
10	2.22	3.2×10^{-4}
11	2.80	4.5×10^{-4}
12	4.78	8.0×10^{-4}

mean	1.33
variance	2.39
median	1.05

[a] calculated at the certainty equivalent

hypothetical lotteries, led to a marked reduction in the variance of the distribution of values of the CPRA for a large sample of subsistence farmers in India. It is likely, therefore, that in a farming situation the range of risk attitudes in Table 4 would contract also; in particular, those individuals at either end of the range might be expected to behave in a more moderately risk-averse manner. Whilst there are obvious dangers in extrapolating results relating to farmers in the semi-arid tropics to cereal growers in New Zealand, such extrapolation is justified, partially at least, by reference to the fact that Binswanger found no statistically significant relationship between increasing wealth and a reduction in the degree of risk aversion.

3.3 Comparison of Expected Monetary Value and the Expected Utility Criteria

Application of the expected monetary value and expected utility criteria will lead to different recommendations only in certain circumstances. The conditions necessary for such differences are dependent primarily on the CPRA and the shape of the yield reduction percentage distribution. (Due to a lack of suitable data, it is assumed throughout that spraying is essentially riskless.) One type of recommendation difference may be identified for an individual who is risk averse: situations will exist where the EMV of not spraying exceeds that of spraying, EMV(NS) > EMV(S), but because of the individual's attitude to risk, the certainty equivalent of spraying is greater than that of not spraying, CE(S) > CE(NS), "spray now" therefore being the utility-maximising strategy. The frequency with which a simulated pdf of yield reduction percentages would lead to differences in recommendation between the EMV and the EU criteria was estimated for the range of risk attitudes in Table 4, using both an analytical and a simulation approach.

3.3.1 Analytical approach

With regard to the analytical approach, any particular yield reduction distribution function, $f(Y_R)$, may be transformed into the money value distribution associated with the strategy of not spraying, $f(x)$; for example, a discrete approximation to $f(Y_R)$, made up of fifty yield loss estimates from fifty different epidemics, would be transformed as follows:

(7) $$x_i = (1-(Y_{R_i}/100)) * P * Y, \quad i = 1, \ldots, 50,$$

where x_i = money value, \$/ha,

Y_{R_i} = yield loss percentage estimate,

P = price expected for barley, \$/t, and

Y = expected healthy yield of barley, t/ha.

A rearrangement of equation (6) gives a cubic equation for $\bar{x}$, the mean value of $f(x)$, in terms of the variance and skewness of $f(x)$, the coefficient of partial risk aversion, and the certainty equivalent of not spraying,

(8) $$\bar{x}^3 - \bar{x}^2(x_o) - \bar{x}(s/2)\mathrm{Var}\,[x] + (M_3\,[x]\,/6)(s^2+s) = 0.$$

The procedure involved the maximisation of $\bar{x}$, and hence the minimisation of $E[Y_R]$, subject to the following constraints:

i) that the EMV and EU criteria led to different recommendations for the same pdf and the same value of the coefficient of partial risk aversion and

ii) that the values of variance and skewness substituted into equation (8) were reasonable, in the sense that they were obtainable from encounters with the information system.

The first constraint was imposed by equating the certainty equivalents of the two strategies, giving the boundary condition CE(NS) = CE(S). For the second, Var [x] and M_3 [x] were assigned "typical" values, and equation (8) was then solved iteratively for $\bar{x}$, x_o being equated with the certainty equivalent of spraying, for various values of the coefficient of partial risk aversion.[3] The root was converted to a percentage yield reduction; this value was then an estimate of the smallest (largest) value of E $[Y_R]$ for a risk averter (risk preferrer) for which the EMV and

3 Values of Var [x] and M_3 [x] are dependent on E [x] to an extent, since $f(Y_R)$, the percentage yield reduction variable, and hence $f(x)$, the associated money value distribution, have well defined upper and lower bounds; there is thus some circularity involved.

the EU criteria just gave the same recommendations, given the variability of the pdf (as defined by its variance and skewness) and the degree of risk aversion.

The results given in Table 5 refer to three levels of variability of the monetary outcome distribution for the strategy of not spraying, f(x). The values of variance and skewness shown were assumed, somewhat arbitrarily, to be representative of high, medium and low levels of variability. As the variability of the pdf decreased, $E[Y_R]$ tended towards the break-even yield reduction, from below for $\underline{s} > 0$ and from above for $\underline{s} < 0$. The approximate probability of occurrence of such yield reduction pdfs, and hence such monetary outcome pdfs, is illustrated in Figure 5. The cumulative distribution function of yield losses was obtained by simulating 6300 epidemics arising from twenty-one combinations of the date of sowing and the date of disease onset (see Chapter 4). If these epidemics are assumed to be representative of all possible epidemics, the cumulative function in Figure 5 may be used to estimate the frequency with which yield reduction pdfs of particular mean values are simulated to occur. If the medium level of variability is taken as the most representative, then the critical range of expected values of the yield loss pdf lies between 3.31 and 5.51 per cent (Table 5); these two values are equivalent to cumulative probabilities of approximately 0.68 and 0.74 respectively (Figure 5). Therefore, the probability of a random encounter with the information system leading to a recommendation difference for at least one value of the coefficient of partial risk aversion in the range -0.70 to 4.78 is of the order of 0.06, if it is assumed that all simulated pdfs with an expected value in the critical range exhibit a variability as large as the medium level of variability defined in Table 5. If the range of risk attitudes is contracted to include values of the CPRA from 0.0 to 2.8 (risk neutrality to moderate risk aversion), this probability decreases to approximately 0.02, for the relevant values of $E[Y_R]$ (4.26 and 5.31 per cent respectively, see Table 5).

3.3.2 Simulation approach

The second method of estimating these same probabilities involved extensive computer simulation; 192 encounters with the information system were carried out, based on 77 simulated leaf rust epidemics. A total of nine encounters exhibited yield reduction pdfs which led to recommendation

TABLE 5

Illustrative Maximum and Minimum Values of the Mean of the Yield Reduction Percentage Distribution, for Three Levels of Variability, for which the EMV and the EU Criteria Lead to Different Recommendations

COEFFICIENT OF PARTIAL RISK AVERSION, S	VALUES OF $E[Y_R]$, % variability high	medium	low	BREAK-EVEN YIELD REDUCTION Y_B, %
-0.70	5.63	5.51	5.36	5.31
-0.14	5.38	5.35	5.33	5.31
0.00	5.31	5.31	5.31	5.31
0.76	4.92	5.06	5.25	5.31
0.98	4.80	4.99	5.23	5.31
1.12	4.72	4.93	5.22	5.31
1.92	4.24	4.63	5.15	5.31
2.22	4.04	4.51	5.12	5.31
2.80	3.65	4.26	5.07	5.31
4.78	2.14	3.31	4.89	5.31
Monetary outcome distributions - no spray:				
Var[x]	8498.5	5483.3	1493.5	
$M_3[x]$	-2463823.2	-1413980.7	-116916.7	

Data used: expected yield = 5.47t/ha; price = $185/t; spray and application costs = $28.45/ha; wheeling damage = 2.5%. It is assumed that spray gives complete control of the rust.

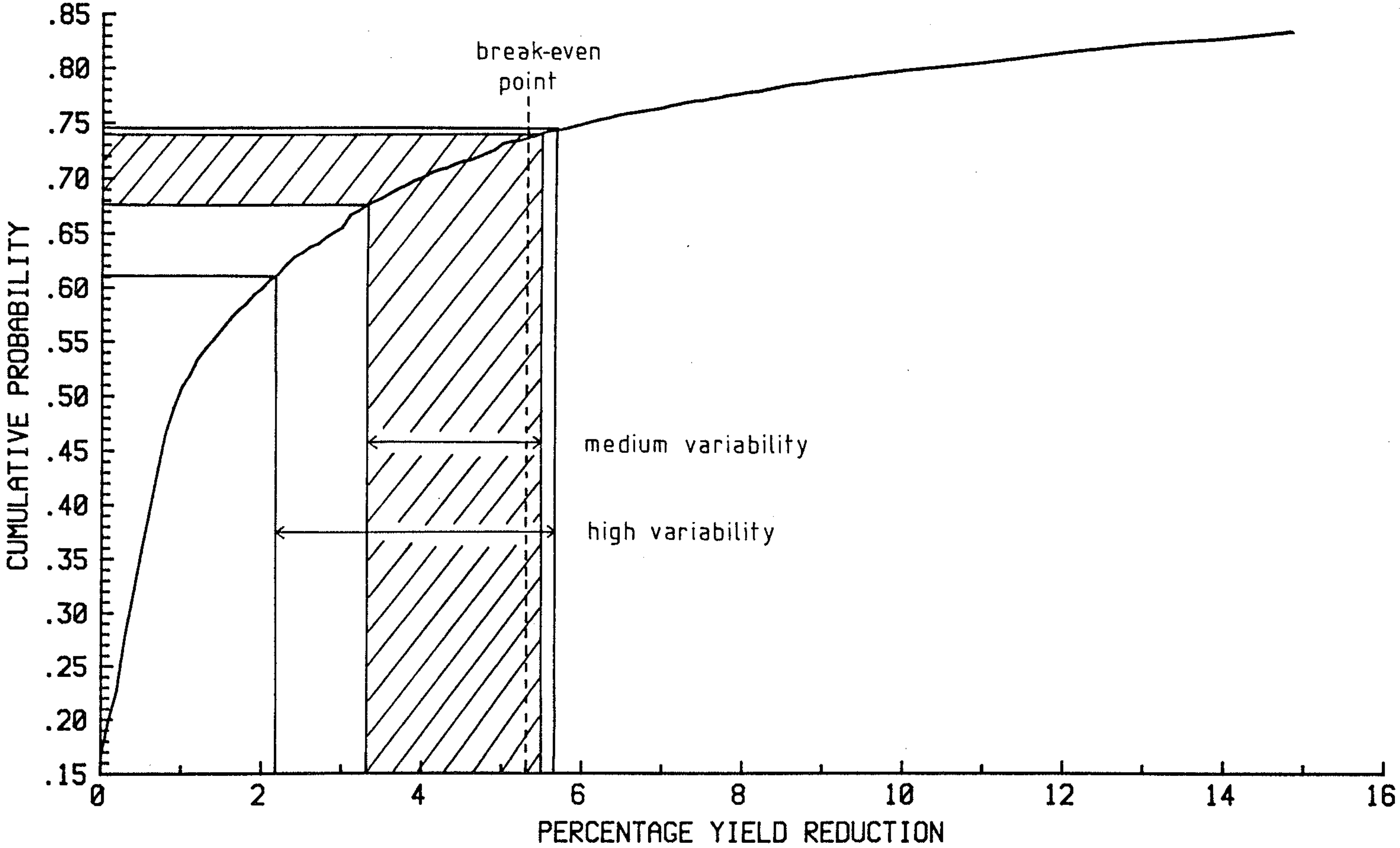

FIGURE 5. Yield Reduction Percentage Cumulative Distribution Function

differences between the EMV and EU criteria for at least one value of the CPRA in the range -0.70 to 4.78, a probability of occurrence of approximately 0.05. Again, on excluding the most extreme risk attitudes by contracting the range of the CPRA from 0.0 to 2.8, five of the 192 encounters resulted in recommendation differences between the two decision criteria, a probability of occurrence of approximately 0.03 (Thornton, 1983).

Both methods gave similar results; the frequency with which application of the EMV and EU criteria could be expected to lead to different recommendations is of the order of one random encounter in twenty, for the range of risk attitudes considered.

3.4 Summary

In most cases, use of the EMV rule will lead to the identification of what, in effect, is the utility-maximising strategy for decision makers of diverse attitudes to risk. The incorporation of personalised utility functions appears to add little to the decision making process; the increase in precision in identifying the "correct" recommendation is spurious, in view of the potential inaccuracies in the simulation components of the information system (the weather parameter, crop growth and leaf rust simulation models). The later in the growing season an encounter with the information system is carried out, the less is the likelihood of the EMV rule leading to the wrong recommendation for a particular individual, since the variability of simulated yield loss pdfs decreases as the end of the growing season is approached.

CHAPTER 4

IMPLEMENTATION

Implementation becomes a crucial issue for any information system claiming to be farm-based. A user of FUNGINFO, in what may be termed an interactive simulation mode, is required to monitor the onset of disease in the field, and to carry out his own disease status assessment, in order to facilitate the revision of the pdf by equating simulated and observed epidemic progress curves on the day of encounter. At a more fundamental level, it is assumed that potential users have access to computing facilities in some form or another. Although circumstances are changing rapidly, under present New Zealand conditions such an assumption would severely limit the potential use of a crop protection information system.

One possible solution to these application difficulties is to use the information system in a development mode to construct tables, which give the recommendation to spray, or to refrain, for particular combinations of conditions and for farmers with different behavioural characteristics. The derivation of such tables is described in this Chapter. The procedure involves the simulation of a large number of possible epidemics to produce prior yield loss distributions for each of a number of combinations of the date of sowing of the crop and the date of disease onset: each epidemic is the result of a particular simulated weather pattern. If a spraying decision is required after a particular number of days have elapsed since disease onset, the prior distribution for the appropriate sowing and disease onset dates is updated, in effect, by grouping the individual epidemic yield reduction estimates into a number of posterior distributions. This may be done on the basis of the occurrence of an easily-measured and relevant environmental criterion over the elapsed number of days subsequent to disease onset. The appropriate recommendation, to spray or to refrain, is then assigned to each updated pdf, for three broad categories of farmer attitude to risk.

4.1 Method

The exact form of the leaf rust yield loss probability density function for a particular crop of barley is assumed to be dependent on an infinite set of weather series, the date of sowing and the date of disease onset. The functional relationship for the yield reduction pdf, $f(Y_R)$, may be written:

(9) $$f(Y_R) = (ISOW, ISTART),$$

where ISOW is the date of sowing and ISTART is the date of disease onset. There thus exists a finite range of prior yield loss distributions, based on a finite number of combinations of these two dates.

It was assumed a priori that small changes in either the date of sowing or the date of disease onset would result in concomitantly small changes in the form of $f(Y_R)$. The possible dates of sowing and disease onset cover the periods 1 October to 31 December for sowing and 1 December to 28 February for onset. Both of these three month periods were arbitrarily subdivided into six approximately equal quantiles, and 21 combinations of sowing date and disease onset date were judged meaningful, in the sense that such epidemics were either possible or of a reasonable duration. These combinations are shown in Table 6. The variability in the form of $f(Y_R)$ between the various combinations shown in Table 6 is dependent primarily on the date of disease onset in relation to the maturity of the crop.

The prior yield reduction percentage distribution was then estimated for each of the 21 combinations of ISOW and ISTART by simulating 300 epidemics for each combination (a total of 6300 epidemics) in response to stochastic weather sequences.

As time advances through the growing season, the form of $f(Y_R)$ for any combination of ISOW and ISTART changes; the addition of historical, hence immutable, weather and disease progress data leads to a posterior pdf, the form of which is principally a function of the age of the crop in relation to the date of disease onset, so,

(10) $$f(Y_R) = (ISOW, ISTART, DATE),$$

where DATE is equated with the date of encounter with the information system. A criterion was required, which could be used as the basis for subdividing the prior yield loss estimates into updated or revised yield loss distributions at different dates of encounter (DATE).

In the construction of the leaf rust simulation model, it was hypothesized that the number of dew days over the first few days of an epidemic had a substantial influence on subsequent yield reduction (Teng,

TABLE 6

Twenty-one Combinations of Date of Sowing and Date of Disease Onset

		Disease Onset Quantile Number (ISTART)					
		1	2	3	4	5	6
Sowing Quantile Number (ISOW)	1	x	x				
	2	x	x	x			
	3	x	x	x	x		
	4	x	x	x	x		
	5		x	x	x	x	
	6			x	x	x	x

Date of Sowing

Quantile midpoint	8 Oct	23 Oct	8 Nov	23 Nov	8 Dec	23 Dec
Quantile number	1	2	3	4	5	6

Date of Disease Onset

Quantile midpoint	8 Dec	23 Dec	8 Jan	23 Jan	8 Feb	23 Feb
Quantile number	1	2	3	4	5	6

1978). The number of days on which dew occurs, indicating those days when spore germination can take place, is suitable as a criterion for subdividing prior yield loss distributions, owing to the relative ease with which it may be measured and correlations established with disease severity. Therefore, the number of simulated dew days experienced within various numbers of days of disease onset was recorded for all 6300 simulated epidemics.

The relationship between the number of dew days and estimated yield reduction percentage was tested using Spearman's coefficient of rank correlation, rho, for the post-onset periods of 7, 15, 25, 35, and 45 days (Table 7). Epidemic length was calculated as the average number of days from onset to Growth Stage 83 attainment (Zadoks, Chang and Konzak, 1974). The poor correlation between yield loss and dew day number in the early stages of long epidemics is apparent; values close to zero were obtained for a number of the combinations of date of sowing and date of disease onset. [Values of rho smaller than 0.113 were not statistically significant ($\alpha = 0.05$) for the sample size of 300 (Conover, 1980).]

For the epidemics of intermediate duration (25 to 46 days), the maximum correlation between yield reduction and dew day number tended to occur approximately half way through the epidemic, rather than occurring at the latest possible time, as might have been expected. The correlation between yield reduction and dew day number, however, is not particularly marked, although rho reached values in excess of 0.5 for all but six of the 21 combinations (Table 7). The highly variable values of rho have implications for the consistency of recommendations in the decision tables.

4.2 The Posterior Distributions and Decision Tables

4.2.1 Onset plus seven days

The first set of posterior yield reduction distributions was derived for each combination of ISOW and ISTART (subsequently here termed a "trial") seven days after disease onset. These pdfs were built up using a subsample of 100 of the total 300 epidemics simulated for each trial, to ensure statistical independence between the decision tables. In view of the relatively rare occurrence of more than three dew days in any seven

TABLE 7

Values of Spearman's Rho at Five Numbers of Days Post-Onset: Correlation Between Percentage Yield Reduction and Number of Dew Days, for Twenty-one Combinations of Date of Sowing and Date of Disease Onset

Quantile Sown	Quantile Onset	Epidemic Length (days)	Values of Spearman's rho — Number of Days After Disease Onset: 7	15	25	35	45
1	1	33	0.43	0.61	0.69	0.58	–
1	2	18	0.77	0.59	0.46	–	–
2	1	44	0.04	0.13	0.15	0.18	0.18
2	2	29	0.60	0.80	0.63	0.51	–
2	3	13	0.76	0.39	–	–	–
3	1	56	0.03	-0.02	0.16	0.34	0.48
3	2	41	0.22	0.57	0.73	0.67	0.56
3	3	25	0.58	0.73	0.59	0.56	–
3	4	10	0.63	0.47	–	–	–
4	1	62	-0.05	-0.04	-0.01	0.21	0.30
4	2	46	0.03	0.18	0.36	0.48	0.44
4	3	31	0.59	0.67	0.61	0.52	–
4	4	15	0.84	0.68	0.62	–	–
5	2	60	0.06	0.17	0.33	0.52	0.61
5	3	45	0.23	0.59	0.64	0.65	0.56
5	4	29	0.44	0.66	0.62	0.53	–
5	5	14	0.64	0.46	0.44	–	–
6	3	57	0.03	0.09	0.34	0.41	0.49
6	4	41	0.40	0.63	0.72	0.71	0.63
6	5	26	0.51	0.59	0.55	0.52	–
6	6	11	0.39	0.18	–	–	–

consecutive days in the period December to February in Canterbury, only four posterior distributions were defined for each trial, for the occurrence of zero, one, two and between three and seven dew days within the seven day period after disease onset. The distributions obtained when each subsample was subdivided according to these occurrences are shown in Table 8. For example, the prior pdf for the trial which was sown in sowing-quantile 1 and on which disease was first observed in onset-quantile 1 had a mean yield reduction of 4.Ø per cent and a variance of 89.5. Of the subsample of 1ØØ replicates, 27 had been simulated where no dew days were experienced in the first seven days of the epidemic; this sample of 27 exhibited a mean of Ø.7 per cent yield reduction and a variance of Ø.9. On the other hand, 22 epidemics were simulated as occurring in conjunction with between three and seven dew days within this period; this sample had a mean yield reduction of 11.4 per cent and a variance of 282.2.

The mean and variance for the four posterior yield loss distributions for all 21 trials are shown in Table 8. The mean values tend to increase as the number of dew days experienced increases. The most noticeable instances of contrary or apparent random movement of the mean with increasing dew day number occur for the longest epidemics, where the correlation between yield loss and dew day number at seven days post-onset is not statistically significant (Table 7).

In order to simplify the decision tables somewhat, it is assumed that the price of barley and the costs associated with spraying will continue in approximately the same ratio as has been exhibited in New Zealand over recent years. An unequivocal recommendation, calculated using the certainty equivalent equations in section 3.1, can be identified for many of the yield reduction distributions in Table 8, regardless of expected yield and attitude to risk. Unambiguous recommendations in this sense, "spray now" (S) or "do not spray" (.), are given in the primary table for onset plus seven days, Table 9. The third type of entry in the primary table consists of an integer, indicating that the yield reduction pdf is of such a form that more information is required from the decision maker before a recommendation can be identified. For such entries, the secondary table, in conjunction with the appropriate integer displayed in the primary table, may be used to obtain the recommendation appropriate to the individual farmer's risk attitude and his estimate of expected yield.

TABLE 8

Yield Reduction Posterior Distributions, Onset plus Seven Days: Mean Percentage and Variance for Twenty-one Combinations of Date of Sowing and Date of Disease Onset

Posterior Distributions - Onset plus Seven Days

Trial Sown	Quantile Onset	Epidemic Length (days)	Dew Day Number 0 Mean	0 Variance	1 Mean	1 Variance	2 Mean	2 Variance	3-7 Mean	3-7 Variance
1	1	33	0.7	0.9	4.5	182.3	6.7	116.6	11.4	282.2
1	2	18	0.1	0.0	1.2	5.0	1.0	0.6	3.0	0.1
2	1	44	12.4	265.7	16.9	198.8	22.9	368.6	14.5	216.1
2	2	29	6.4	25.7	25.2	228.0	25.3	30.0	30.7	67.1
2	3	13	0.4	0.0	1.4	7.7	1.7	4.3	3.7	12.5
3	1	56	15.7	158.8	23.6	289.0	22.5	299.3	16.8	269.0
3	2	41	15.2	169.0	16.9	272.3	37.5	295.8	21.8	888.0
3	3	25	2.6	18.9	11.2	74.5	17.8	33.5	14.9	62.6
3	4	10	0.3	0.0	0.6	0.1	1.6	3.7	2.4	8.4
4	1	62	4.9	108.2	2.1	10.3	1.5	9.0	4.7	134.6
4	2	46	3.3	59.9	4.4	44.4	10.0	364.8	4.3	7.0
4	3	31	1.1	4.6	4.1	54.8	5.1	29.8	5.1	17.4
4	4	15	0.0	0.0	0.4	0.3	0.6	0.2	2.1	7.4
5	2	60	6.5	100.0	10.7	324.0	8.7	96.2	2.0	0.0
5	3	45	3.9	54.5	8.5	144.0	11.4	237.[illegible]	14.3	392.0
5	4	29	0.5	0.6	1.1	2.4	4.4	72.3	5.6	62.4
5	5	14	0.2	0.0	0.7	0.5	0.7	0.0	0.8	0.2
6	3	57	6.9	125.4	11.3	269.0	11.1	313.3	3.9	18.1
6	4	41	2.9	24.6	8.8	108.2	13.5	424.4	19.7	400.0
6	5	26	0.4	0.4	2.1	15.0	1.5	3.4	4.4	19.3
6	6	11	0.1	0.0	0.3	0.1	0.5	0.1	0.6	0.2

TABLE 9

Decision Tables - Onset plus Seven Days

P R I M A R Y   T A B L E

QUANTILE Sown	Onset	DEW DAYS OBSERVED Ø	1	2	3 - 7
1	1	.	1	2	S
	2	.	.	.	.
2	1	S	S	S	S
	2	3	S	S	S
	3	.	.	.	.
3	2	S	S	S	S
	3	.	S	S	S
	4	.	.	.	.
4	2	.	4	S	.
	3	.	5	6	7
	4	.	.	.	.
5	3	.	S	S	S
	4	.	.	8	9
	5	.	.	.	.
6	4	.	S	S	S
	5	.	.	.	1Ø
	6	.	.	.	.

Note: "." do not spray, "S" spray, "i" enter secondary table on right, at i and expected yield.

S E C O N D A R Y   T A B L E

Number	EXPECTED YIELD, T/HA 3	4	5	6	7	8
1	*	*	x	x	x	S
2	*	S	S	S	S	S
3	.	S	S	S	S	S
4	.	.	.	.	*	x
5	.	.	.	.	*	x
6	.	.	.	S	S	S
7	.	.	.	S	S	S
8	.	.	.	*	x	S
9	.	.	x	S	S	S
1Ø	.	.	.	.	.	S

Note: "." do not spray, "S" spray, "*" spray if severely risk averse, "x" spray if at least moderately risk averse.

The four combinations of sowing date and onset date with epidemic lengths in excess of 55 days are excluded from the table on account of their poor yield loss-dew day number correlations.

The recommendations in the secondary table are derived for integer values of expected yield in the range 3.Ø to 8.Ø tonnes per hectare. The appropriate recommendation may be identified for individuals who are risk neutral, moderately risk averse or severely risk averse. For the latter two categories, the results of the survey of farmers' risk attitudes described in Chapter 3 were used to define representative behaviour, in terms of the coefficient of partial risk aversion (CPRA) (Thornton, 1983). The median of the elicited values of the CPRA was identified with the moderately risk averse category, while a CPRA twice as large was used to identify the utility-maximising strategies for the severely risk averse decision maker. There are therefore four types of recommendation in the secondary table: spray regardless of risk attitude, "S"; do not spray, regardless of risk attitude, "."; spray only if severely risk averse, "*"; and spray if at least moderately risk averse, "x".

Use of the tables may be illustrated by considering a barley crop planted during the period 1 to 15 October (sowing-quantile 1) on which disease was first observed during the period 1 to 15 December (disease onset-quantile 1). If no dew days were experienced in the seven days subsequent to onset, spraying would not be recommended, from the primary table, Table 9. If, however, one dew day was experienced within this period, the secondary table would be consulted; entering from the left on line 1, it could be seen that spraying would be recommended for all severely risk averse individuals, regardless of expected yield in the range 3 to 8 tonnes per hectare. If the individual was only moderately risk averse, spraying would not be recommended for expected yields of 4 t/ha or less; at an expected yield level of 8 t/ha, all individuals should spray, regardless of attitude to risk.

4.2.2 Beyond onset plus seven days

The same process of deriving posterior distributions and identifying the appropriate recommendation for each distribution was repeated for three additional sets of decision tables; these were designed to provide recommendations at 15, 25 and 35 days post-onset. A number of the trials are not included in the last two sets, since the epidemics had finished before the appropriate date. Five posterior distributions were defined for each trial at each encounter date, Tables 10 to 12. The changing distribution of dew day occurrence over the period December to March made it impossible to define a single dew day number classification suitable for all trials within each set of decision tables. For instance, there were insufficient simulated epidemics relating to zero dew days within 15 days of onset to define a posterior pdf based on this event for five of the 21 trials. The first posterior pdf for these five trials thus included all epidemics which experienced zero or one dew day within the first 15 days of the epidemic, Table 10. Five dew day event classifications had to be used for the decision tables derived at both 25 and 35 days post-onset, so that there were a sufficient number of simulated epidemics within each classification with which to define the posterior pdfs.

4.3 Value of Decision Tables

The worth of information may be measured as the maximum price a decision maker could pay for it and still remain as well-off, in utility terms, as if he had not had access to the information (Byerlee and Anderson, 1982). This definition may be restated in terms of certainty equivalents: the value of the recommendations produced using the spray decision tables may be approximated as the difference between the certainty equivalents of the prior and posterior utility-maximising strategies.

For lack of more suitable data, the 6300 simulated epidemics used in the derivation of the spray tables may be taken as constituting the prior yield reduction distribution (see Figure 5). The appropriate recommendation pertaining to this pdf was found by calculating the certainty equivalent of each of the two strategies, for a particular set of data, i.e., the price received for barley was \$185/t, the spray material and application costs were \$28.45/ha, spraying brought about a yield loss of 2.5 per cent due to wheeling damage, the expected yield was 5 t/ha, and the first three moments of the yield reduction distribution were 6.3 per cent, 123.4 and 3530.7 respectively. The utility-maximising strategy was found to be "spray now" for all values of the coefficient of partial risk aversion in the range elicited in the farmer survey (Thornton, 1983).

TABLE 10

Decision Tables - Onset plus Fifteen Days

P R I M A R Y   T A B L E

QUANTILE Sown	Onset		DEW DAYS OBSERVED 0	1	2	3	4 - 15
1	1		.	.	.	1	S
	2		.	.	.	.	.
2	1		2	S	S	S	S
	2		.	S	S	S	S
	3		.	.	.	.	.
3	1		S	S	S	S	S
	2		3	S	S	S	S
	3		.	4	S	S	S
	4		.	.	.	.	.
4	1		5	6	.	S	7
	2		.	.	8	S	.
	3		.	.	.	.	9
	4		.	.	.	.	.
5	2		.	10	S	.	S
	3	*	.	.	.	S	S
	4	*	.	.	.	S	S
	5		.	.	.	.	11
6	3	*	.	12	.	13	S
	4	*	.	.	S	S	S
	5	*	.	.	.	14	15
	6		.	.	.	.	.
	(dew days	*	0-1	2-3	4-5	6-7	8-15)

Note: "." do not spray, "S" spray, "i" enter secondary table on right, at i and expected yield.

S E C O N D A R Y   T A B L E

Number	EXPECTED YIELD, T/HA 3	4	5	6	7	8
1	.	x	S	S	S	S
2	.	.	S	S	S	S
3	.	.	*	S	S	S
4	.	S	S	S	S	S
5	*	x	S	S	S	S
6	.	*	*	x	x	x
7	.	*	*	x	x	x
8	*	*	x	x	x	x
9	x	S	S	S	S	S
10	*	x	S	S	S	S
11	.	.	.	x	S	S
12	*	S	S	S	S	S
13	*	x	S	S	S	S
14	.	.	.	*	S	S
15	.	.	*	S	S	S

Note: "." do not spray, "S" spray, "*" spray if severely risk averse, "x" spray if at least moderatelv risk averse.

TABLE 11

Decision Tables - Onset plus Twenty-Five Days

PRIMARY TABLE

QUANTILE Sown	Onset		DEW DAYS OBSERVED 0 - 1	2	3	4	5 - 25
1	1		.	.	.	1	S
2	1		S	S	S	S	S
	2		2	S	S	S	S
3	1		S	S	S	S	S
	2		.	S	S	S	S
	3	*	.	3	S	S	S
4	1		.	4	.	.	S
	2		.	.	5	.	6
	3	*	.	.	.	.	S
5	2		.	7	8	S	.
	3	*	.	.	9	S	S
	4	#	.	.	.	10	S
6	3	*	.	11	S	S	S
	4	@	.	.	12	S	S
	5	%	.	.	.	13	.
	(dew days :	*	0-1	2-3	4-5	6-7	8-25
		#	0-3	4-5	6-7	8-9	10-25
		@	0-2	3-4	5-6	7-8	9-25
		%	0-4	5-6	7-8	9-10	11-25)

Note: "." do not spray, "S" spray, "i" enter secondary table on right, at i and expected yield.

SECONDARY TABLE

Number	EXPECTED YIELD, T/HA 3	4	5	6	7	8
1	*	x	S	S	S	S
2	.	S	S	S	S	S
3	.	.	.	.	.	x
4	.	.	.	*	x	S
5	.	.	.	.	.	*
6	.	x	S	S	S	S
7	.	.	*	x	x	S
8	*	S	S	S	S	S
9	x	S	S	S	S	S
10	.	.	.	.	.	x
11	.	.	.	.	.	*
12	.	.	x	S	S	S
13	.	.	S	S	S	S

Note: "." do not spray, "S" spray, "*" spray if severely risk averse, "x" spray if at least moderately risk averse.

TABLE 12

Decision Tables - Onset plus Thirty-Five Days

PRIMARY TABLE

QUANTILE Sown	Onset		DEW DAYS OBSERVED Ø - 2	3	4	5	6 - 35
1	1		.	.	1	2	S
2	1		S	S	S	S	S
3	1		S	S	S	S	S
	2	*	.	S	S	S	S
4	1	*	.	.	.	.	S
	2	#	.	.	.	3	S
	3	@	.	.	.	.	S
5	2	*	.	.	4	S	S
	3	@	.	.	5	6	S
6	3	@	.	.	S	7	S
	4	%	.	.	8	S	S
	(dew days	*	Ø-1	2-3	4-5	6-7	8-35
		#	Ø-2	3-4	5-6	7-8	9-35
		@	Ø-3	4-5	6-7	8-9	1Ø-35
		%	Ø-4	5-6	7-8	9-1Ø	11-35)

Note: "." do not spray, "S" spray, "i" enter secondary table on right, at i and expected yield.

SECONDARY TABLE

Number	EXPECTED YIELD, T/HA 3	4	5	6	7	8
1	*	x	S	S	S	S
2	*	x	S	S	S	S
3	.	.	*	S	S	S
4	.	x	S	S	S	S
5	.	x	S	S	S	S
6	x	S	S	S	S	S
7	.	.	x	S	S	S
8	.	.	.	.	*	S

Note: "." do not spray, "S" spray, "*" spray if severely risk averse, "x" spray if at least moderately risk averse.

Clearly, the spray tables have value only in those circumstances where the posterior utility-maximising strategy is different from the prior utility-maximising strategy, otherwise the decision maker has obtained no benefit from the use of the additional information.

In the identification of the posterior utility-maximising strategies, all 6300 epidemics from the twenty-one combinations of ISOW and ISTART (Table 6) were subdivided into posterior pdfs at 7, 15 and 25 days post-onset. The estimated worth of the information contained in the spray tables (presented in Table 14) is thus an average value. The value of the spray tables to a particular farmer in a particular season may be slightly over-estimated or grossly under-estimated: for some combinations of ISOW and ISTART, the tables have no value, since the posterior utility-maximising strategy for all posterior pdfs is the same as the prior utility-maximising strategy. On the other hand, some combinations exhibit posterior pdfs for which the mean value of yield reduction is close to zero, regardless of dew day number; the value of the posterior "do not spray" recommendations is then relatively high.

The posterior utility-maximising strategies were identified 7, 15 and 25 days post-onset (Table 13). For example, the three posterior distibutions obtained in response to one or more dew days in the seven days post-onset were of such a form that the certainty equivalent of spraying exceeded that of not spraying, regardless of the value of the coefficient of partial risk aversion used (Table 13). This was not the case for the zero dew days pdf, however, where the utility-maximising strategy was dependent on the degree of risk aversion.

The value of the decision tables derived 15 days post-onset, for example, may then be calculated as

(11) $$V_{15} = (CE(NS) - CE(S)) * 0.15,$$

since the recommendation "do not spray" is obtained only if zero dew days are experienced; the probability of zero dew days is approximately 0.15, for the period December through February.

The value of the spray tables is estimated in Table 14, for individual farmers with a coefficient of partial risk aversion in the range -0.70 to 4.78 and for posterior distributions which did not suggest an unequivoval "spray now" recommendation in Table 13. In each case, the value of information derives only from those instances where the posterior and prior

TABLE 13

Posterior Utility-Maximising Strategies at Three Dates Post-Onset

7 Days Post-Onset

Number of dew days, i	0	1	2	3–7
Probability of i dew days	0.37	0.29	0.17	0.17
Recommendation	+	S	S	S

15 Days Post-Onset

Number of dew days, i	0	1	2	3	4–15
Probability of i dew days	0.15	0.21	0.20	0.16	0.28
Recommendation	NS	S	S	S	S

25 Days Post-Onset

Number of dew days, i	0	1	2	3	4–25
Probability of i dew days	0.06	0.13	0.17	0.15	0.49
Recommendation	NS	+	S	S	S

Note: S = spray now; NS = do not spray; + = decision dependent on coefficient of partial risk aversion in the range −0.70 to 4.78.

TABLE 14

The Value of Information in Terms of Certainty Equivalents, Dollars per Hectare, for Six Values of the Coefficient of Partial Risk Aversion at Three Dates Post-Onset

Coefficient of Partial Risk Aversion		4.78	2.22	1.12	0.76	0.00	-0.70
Onset + 7 days							
	0 dew days	-	-	0.77	1.49	2.88	4.01
Onset + 15 days							
	0 dew days	0.25	2.02	2.62	2.79	3.13	3.41
Onset + 25 days							
	0 dew days	1.18	1.71	1.89	1.93	2.03	2.09
	1 dew day	-	1.37	1.93	2.10	2.42	2.68
	(total)	1.18	3.08	3.82	4.03	4.45	4.77

Note: values given are (CE(NS) - CE(S))*p_i.

utilty-maximising strategies differ. The value of any encounter increases with decreasing partial risk aversion, since the value is dependent on the recommendation not to spray, risk-averse individuals being loth not to apply spray (increasingly loth with an increasing value of the CPRA). The value of successive encounters tends to increase, as might be expected, with the concomitant reduction in the variability of the yield reduction pdf as the day of encounter moves forward through time. Despite the crudity of the estimation procedure, it is apparent that while the primary economic benefits of the spray decision tables are not particularly great, they are not insignificant. (However, the secondary costs associated with spraying, whilst difficult to quantify, may have a considerable effect on any estimates of the value of such information.)

4.4 Assessment of the Decision Tables

A number of inconsistencies are apparent in the decision tables presented in Tables 9 to 12. For instance, consider the recommendations applicable 15 days post-onset for a crop sown in quantile 4 with disease onset occurring in quantile 2. Spraying is recommended if three dew days are observed in the 15 day period, whilst no action is recommended if a greater number of dew days is experienced. Such inconsistencies are attributable primarily to poor correlation between yield loss and dew day number; the use of sample sizes greatly in excess of 100 simulated epidemics might have a smoothing effect on the upward trend of the mean with increasing dew day number.

Of more importance is the nature of the events used to characterise the posterior yield loss distributions. The relative ease with which dew day number can be measured constitutes a major advantage of the use of such a weather parameter in an information system context. More extensive analysis investigating the correlation between yield reduction and a suitable criterion might reasonably be carried out. Joint meteorological and epidemiological occurrences might be investigated and their correlation with final yield reduction examined. For example, improved values of the correlation coefficients might be obtainable from a consideration of dew day number in conjunction with cumulated average ambient temperature, or from dew day number and some measure of the disease present on the day a decision is required.

There are advantages to this latter procedure, since it would be desirable to relate observed field conditions to the decision making process in some way, especially when appreciable lengths of time elapse between disease onset and the day a recommendation is required. This suggests the possibility of more sophisticated decision tables; while it defeats the objectives of such tables to make them totally situation-specific, there are no conceptual barriers which prohibit the incorporation of observed disease levels, for example, as well as dew day number. The costs of such additions reside principally in the monetary costs of derivation and in a more complicated procedure for the decision maker. A delicate trade-off would appear to be necessary in the construction of these tables, since ease of use may well be inversely related to the production of timely, valid recommendations.

Tables for the spray decision might be expected to be most useful in situations where the effects of their drawbacks could be minimised: where an early-warning of a potentially damaging epidemic is needed, and where this warning needs to be obtained with minimal use of computing facilities, with minimal cost, and with minimal input of time and effort on the part of the decision maker.

CHAPTER 5

CONCLUSIONS: SIMULATION MODELS AND INFORMATION SYSTEMS

The primary simulation component in FUNGINFO is the leaf rust simulation model. It may be viewed as a black box which accepts weather and crop growth details, and produces valid output (a yield reduction percentage) by a particular method. Conceptually, any other barley leaf rust simulation model could be substituted for the one presently used; it might be simpler or more complex in design, or use totally different means of achieving the same end. The information system was built around the existing leaf rust simulation model, the workings of which were deemed irrelevant to the information system as a whole. In this Chapter, the concept of interchangeable simulation components is developed, by considering firstly the nature of biological models and the information systems in which they may be embedded, and secondly how the utility of an information system such as FUNGINFO might be assessed.

5.1 Design Criteria

Certain general characteristics may be identified which should be exhibited by the simulation components within the context of an information system:

(1) much of the input data necessary for an encounter with the information system should be capable of being generated within the information system itself. This characteristic can help to alleviate problems relating to the provision of data by the user. For example, the day-to-day simulation of the development of the rust requires green leaf area curves for the top two leaves of the primary tiller; these are modelled using regression functions which relate leaf area to the number of days post-emergence.

(2) it should be possible to adjust simulation components in a meaningful fashion in the light of actual occurrences. With regard to the crop protection information system, this characteristic embodies two distinct features: the need for effective methods of updating simulated epidemic progress and simulated crop growth, in response to the actual levels of disease and the physiological age of the crop, and the requirement that it be possible to incorporate the effects of different crop protection strategies on subsequent yield. The leaf rust simulation model used in FUNGINFO exhibited this characteristics to a limited degree only, a direct

consequence of the fact that the design criteria which spawned the model and those that gave rise to the information system were not the same. It would appear desirable to design the information system before the detailed biological component is considered; the full specification of the major simulation model is unlikely to be known with certainty until the framework in which it is to be embedded has been finalised.

(3) a third major characteristic is concerned with the nature of the relationships used in the construction of biological models. It is useful to draw a distinction between empirical and mechanistic (or causal) models, that is, either those that are built on the basis of relationships which link two or more phenomena with no particular regard for the actual mechanisms of the process, or those that are built to represent the mechanisms themselves. (It may be noted that almost all simulation models will fall between these two extremes; the distinction between empirical and causal models tends to be one of degree, in practice). A distinct advantage to the incorporation of causal relationships within a biological model is that it is then possible to use the resultant model under different conditions from those which prevailed when the relationships were developed. A problem with a model built around empirical relationships is that, if it should prove necessary to modify it in any way, for example in an attempt to extend its applicability, it is unknown *a priori* to what lengths such modifications can be carried before the (empirical) validity of the relationships between input and output is destroyed.

5.2 Utility of an Information System

In general, the utility of an information system, measured by the extent to which it is implemented, is dependent principally on the validity and the value of the information produced. Validity relates to the inherent appropriateness of the abstract relationships used to model the relevant phenomena; information has value because of its ability, in a decision making context, to lead to decisions which are different from those which would have been taken in its absence.

The value of the recommendations produced by the leaf rust information system may be estimated in dollar terms for particular individuals (see section 4.3). The subjective element inherent in the concept of value may be equally important; this involves an acknowledgement by potential users that the information produced goes some way to solving a perceived problem.

The validity of information is a function of the methods used in its derivation, inter alia. The meaning of validity, and the kinds of techniques which may be used to establish or refute validity, remain complex problems. The limitations of traditional statistical criteria have been recognised in relation to the validation of simulation models (Dent and Blackie, 1979; Greig, 1979). There would appear to be some benefit to be gained from viewing a model's validity in Bayesian terms: the extent to which the resultant information is used in a decision making process may be explained by the extent to which the user's degree of belief is modified by the assimilation of the information in question. For example, an encounter with the leaf rust information system will either reinforce the user's perception of the damage likely to occur to his barley crop, if the recommendation is in accord with his prior perception, or it will run counter to his prior perception. In the latter case, the action that is actually taken will be dependent primarily on the individual's attitude to the information system; the statistical validity of the recommendation itself may be of little importance. As in many validation exercises, subjective belief in the value of the information system will be either reinforced or destroyed when the recommendations produced using the information system can be checked against the action that should have been taken with the benefit of hindsight (perfect information).

There is unlikely to be any simple relationship between the statistical validity and the perceived value of a model: in the first place, an unchanging level of validity inheres in a particular model, whereas the perceived value may fluctuate, quite possibly for no apparent reason; secondly, a statistically valid model is capable of delivering wrong information (that is to say, there is no perfect predictor).

Statistical validity alone may be insufficient to guarantee the use of an information system; conversely, the perceived value of an information system may be far in excess of its actual ability to influence decision making for the better. A considerable responsibility, therefore, rests with the modeller to ensure that his models exhibit a high level of validity. Whilst they may be difficult to quantify, secondary costs may be incurred through allowing an invalid model to influence to a significant degree the user's prior probability distribution of possible outcomes. These secondary costs consist of carry-over costs arising directly from the use of wrong information, which could be vast for a model of the agricultural sector used to shape government policy, for instance, and the opportunity costs which arise because users are henceforth reluctant to use any computer-based management aid. Validity would appear to be more onerous to demonstrate or refute in relation to empirical models, if only because there is already a degree of validity in a satisfactory causal model: a mechanism which explained the facts, as it were, would tend to be valid per se.

* * *

The incorporation of causal relationships in biological models is associated with two major benefits: such models may be easier to validate or invalidate, making it easier for the modeller to meet his responsibilities to future users of his model, and the applicability of such models may be extended beyond the conditions which prevailed when the model was built. FUNGINFO makes use of a simulation model which was constructed on the basis of field experiments on one cultivar of barley in two growing seasons. A useful extension, therefore, would be the development of a disease model which could simulate the spread of the rust on many diverse cultivars of barley. It might then prove possible to incorporate different diseases in the same general framework, and ultimately, links might be established between the fungus:crop interactions of a number of similar leaf diseases of cereals.

The identification of links between various systems which function for the same purpose, or which have strong analagous characteristics, may be seen as one of the fundamental roles of the application of systems theory (von Bertalanffy, 1968). This role was illustrated in a paper by Boulding (1953) on the quest for a unified general theory of growth: the growth phenomenon is ubiquitous, and the classification of forms of growth cut across the conventional disciplinary boundaries. The use of information systems and carefully designed biological simulation models have much to offer in the planning and direction of agricultural research and in the transmission of the results to farmers.

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